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Performance Assessment of Smart Distribution Networks with Strategic Operation of BEVs

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Abstract—Energy security, greenhouse gas emission, and debate on climate change gained an increased interest for penetrating renewable power generation into distribution networks. Among the renewable power technologies, the wind power takes a considerable share to supply the electricity demand in many networks. The wind is intermittent and its power output needs an auxiliary support to serve the energy customers and to limit impacts. The emerging battery electric vehicles (BEVs) are a potential source that can be used to mitigate intermittent effects of wind power outputs in modern distribution networks. BEVs are inherited with the mobility advantage and they can be used as a battery-based energy storage solution to smooth intermittent power outputs. Taking into account the mobility advantage of BEVs, the paper investigates the strategic ability of them to enhance the reliability performance of an unbalanced power distribution network by incorporating the provision of smart coordination of vehicles. Operation of BEVs are characterized by using charging and discharging rates, depth of discharge, and their states of charge at times of operation. A set of case studies were performed by integrating generic distribution network models to a power transmission network model. The results suggest that strategic operation of BEVs can potentially provide a considerable opportunity to build capacity required for wind power in smart power distribution systems. Results also depict that the necessary BEV capacity to mitigate wind impacts on reliability does not necessarily correlate with installed capacities of wind plants. A quantitative assessment provides detailed information of impact thresholds.

Index Terms—Intermittency of wind power, battery electric vehicles, plug in hybrid electric vehicles, reliability indices, time series

Nomenclature

C	Wind regimes correlation factor
CG_t	Conventional power generation at time t
C_t	BEVs output power at time t
DOD	Depth of discharge
L_t	Load demand at time t
P_t	Battery charging/discharging capacity at time t
R	Charging and discharging rate
S	Distance between wind farms
SOC	State of charge
SG_t	Surplus power generation at time t
SOC_t	Battery state of charge at time t
SOC_{max}	Upper limit of battery state of charge
SOC_{min}	Lower limit of battery state of charge
WG_t	Generated power of wind plant at time t
η	Efficiency

I. Introduction

Traditional power systems were designed by taking into account the notion of central power transports energy to distributed load centers via transmission corridors. With the transformation of passive power networks into active power networks, the network demand is also supplied by the embedded generation that includes wind. In most modern power systems, the wind based power generation shares a considerable load demand compared with other renewables. In any power system, the reliability of power supply to customers is the prime driver that cannot be compromised over the increased presence of intermittent power generation, including wind. There are remedies to mitigate effects of intermittent power outputs of renewable power generation, however they are not always economical and often increase the investment horizons of costs.

Emerging BEVs offer wider benefits, including clean energy generation and dynamic energy storage using their mobility advantages. They can also provide standing reserve supports when they are integrated to a power network. On the other hand,

the other energy storage solutions can also be used as standing reserve resources to mitigate effects of intermittent outputs. However, those solutions can also carry a significantly-high investment costs, time, and space limitations, which may not always be justified in a business case.

The published literature addresses positive and negative impacts of BEVs related to power distribution systems. The influence of BEVs for the reduction of energy loss, the load profile variation, and peak shavings are explored in [1]. BEVs that are used as a controllable load to mitigate voltage fluctuations of feeders with the injection of photovoltaic generation is investigated in [2]. Reference [3] explores BEVs as an energy storage medium to smooth outputs of intermittent wind power generation. Reference [4] concludes that much higher levels of wind power can be absorbed by a power system with of BEVs. Energy and cost savings available to vehicle owners are analyzed in [5]. Intermittent effects of distributed generation are investigated in [6]. Strategic value of intermittent distributed generation is explored in [7] and it argues that the security supply can potentially be enhanced with the strategic use of wind power. Reliability of a power system is another critical issue brought by the integration of BEVs [8]. Reference [9] suggests that the BEVs can serve as a backup generation medium to serve peak power and storage medium to improve reliability of renewable integrated power systems. Study on the vehicle-to-grid effects on the energy not supplied (ENS) is performed in [10]. Reference [11] investigates the energy cost saved by reducing ENS with different BEV penetration scenarios.

This paper characterizes the detailed operation of BEVs using time series models and then proposes a methodology to assess the reliability performance in a smart wind-integrated unbalanced power system with strategic BEVs. The approach considers that the smart network comprises of smart control and coordination facility to manage the volume and locations of BEVs as per the need. BEVs are used as a strategic source to enhance the accommodation capacity of wind power generation. The approach incorporates failure mode and effect analysis to quantify impact thresholds of reliability of power supply. The operation of BEVs is modelled as a time-sequential model that incorporates state of charge, depth of discharge, and charging and discharging rates. Generic distribution network architectures are developed and connected to IEEE 24 bus test system to integrate BEVs. The specific contribution of this paper is the incorporation of unbalance network analysis into failure mode and effects analysis routines and then analyzing a power system as a whole system by incorporating central generation, transmission, distribution, and embedded generators.

II. Modelling BEV characteristics

A. Battery system in BEVs

The criterion that is adopted for the operation of BEVs is whenever the generation exceeds a load-demand; the surplus energy has to be stored in the batteries of BEVs and the stored energy is to be used whenever there is a deficit in power generation. The maximum charging and discharging rates of the batteries determine the maximum amount of energy that can be exchanged between the BEVs and the power grid during a time-step. The battery SOC time series is obtained by using the surplus generation time series while considering the charging and discharging rates, efficiency, and losses that occur during the process. These parameters are used to model the operating characteristics of BEVs. Following sections detail the specific procedures adopted for characterizing batteries in BEVs.

Step 1: Calculation of energy deficit

This step determines the time series of surplus power generation $\{SG_t; t = 1, 2, \dots, T\}$ from the time series of conventional power generation $\{CG_t; t = 1, 2, \dots, T\}$, time series of wind plant power generation $\{WG_t; t = 1, 2, \dots, T\}$ and the time series of the load demand $\{L_t; t = 1, 2, \dots, T\}$ using (1). The positive value of SG_t represents the generation power exceeds load demand, while the negative value of SG_t indicates that the generation is insufficient to meet the load demand. [12]

$$SG_t = CG_t + WG_t - L_t \quad (1)$$

Step 2: Calculation of required import/export capacities of batteries

Whether the surplus power generation SG_t can be fully absorbed is determined by the charging and discharging rates and the spare capacities of batteries. This step is used to calculate the time series of the battery capacities $\{P_t; t = 1, 2, \dots, T\}$ which can be exchanged between the BEVs and the grid, considering the charging and discharging rates while upgrading the battery capacity limits to capture the required capacities. The outcome of this step is used in Step 3 and Step 4 to generate actual SOC time series of batteries of BEVs and then to calculate the output power time series.

If the maximum charging and discharging rate is considered as R and the total efficiency during the process is considered as η , then for the time period Δt ($\Delta t = 1$ in this case because $t = 1, 2, \dots, T$), the total energy $P\Delta t$ extracted from or stored into batteries is given by (2).

$$-R\Delta t/\eta \leq P_t\Delta t \leq R\Delta t\eta \quad (2)$$

In (2), a positive value of $P_t \Delta t$ indicates that the energy is imported to the batteries while a negative value indicates that the energy is exported from batteries. Hence, SG_t and $P_t \Delta t$ can be mathematically formulated as in (3).

$$P_t \Delta t = \begin{cases} SG_t \Delta t \eta & \text{if } 0 \leq SG_t \Delta t \leq R \Delta t \\ \frac{SG_t \Delta t}{\eta} & \text{if } -R \Delta t \leq SG_t \Delta t < 0 \\ R \Delta t \eta & \text{if } SG_t \Delta t > R \Delta t \\ \frac{-R \Delta t}{\eta} & \text{if } SG_t \Delta t < -R \Delta t \end{cases} \quad (3)$$

Step 3: Calculation of time series of battery state of charge $\{SOC_t; t = 1, 2, \dots, T\}$

In order to increase the battery lifetime, the battery rating is also given with the maximum DOD. In addition, there is a reserved capacity to use in road consumptions of BEVs. Hence SOC_{min} is the combination of DOD and reserved capacity. The battery is also constrained by the total capacity SOC_{max} . Thus, SOC_t varies as in (4).

$$SOC_{min} \leq SOC_t \leq SOC_{max} \quad (4)$$

Then, after a time interval Δt the battery state can be given as in (5).

$$SOC_t = \begin{cases} SOC_{max} & \text{if } SOC_{t-1} + P_t \Delta t \geq SOC_{max}, \\ SOC_{min} & \text{if } SOC_{t-1} + P_t \Delta t \leq SOC_{min}, \\ SOC_{t-1} + P_t \Delta t & \text{else} \end{cases} \quad (5)$$

Step 4: Calculation of time series of actual BEVs power output $\{C_t; t = 1, 2, \dots, T\}$.

Step 2 only considers the surplus energy that can be exchanged if SOC is disregarded. After Step 3, the actual output power of BEVs can be calculated as in (6),

$$C_t \Delta t = \begin{cases} (SOC_t - SOC_{t-1}) / \eta & \text{if } SOC_t > SOC_{t-1}, \\ (SOC_t - SOC_{t-1}) \eta & \text{if } SOC_t < SOC_{t-1}, \\ 0 & \text{else} \end{cases} \quad (6)$$

where, positive and negative C give charging and discharging respectively.

B. Deterministic modelling of Aggregated volume (bulk volume) of BEVs

BEVs can offer hybrid benefits by acting as non-stationary units for transportation and stationary units for the benefits of distribution networks. BEVs are not always stationary and can also be connected to a grid. Survey conducted in [13] found that the average personal vehicle in use takes only a 4% of a day while leaving 96% of the day in idle condition, and a single vehicle travels a daily average distance of about 50km. Investigations in [2] also suggest that over 92% of vehicles are parked even during peak traffic hours. If assume that stationary BEVs are all connected to the grid, the behavior of a large fleet of aggregated volume of BEVs can be highly predictable [14]. This approach assumes that the BEVs connected at a single location (e.g., 11kV bus) can be represented as an aggregated volume taking into account the facilities of smart coordination and control options. The number of BEVs at an aggregated volume is considered as 1250 as per the conversations with practicing engineers and the designed capacity at charging/discharging stations remains constant in a normal day. However, it is also possible to incorporate different BEV capacities at the connecting nodes in the power network and in that context the charging and discharging levels of BEVs at stations vary depend on the operating circumstances including weather conditions, road congestions, individual's business models, and other operating constraints.

The proposed approach considers the energy capacity of a battery electric vehicle as 80kWh with a maximum charging and discharging rate of 16kW [15]. Thus, the aggregated volume of BEVs at a single node have a total battery energy capacity of $80\text{kWh} \times 1250 = 100\text{MWh}$ and the maximum rate of $16\text{kW} \times 1250 = 20\text{MW}$. The charging and discharging losses are assumed as 6% and the line losses are assumed as 4%, hence the total efficiency of the system (η) is 90%. Single BEV daily-commute distance is assumed as 40km and on road energy consumption of a battery is 0.2kWh/km. Therefore, $0.2\text{kWh} \times 40 = 8\text{kWh}$ of single BEV battery energy is reserved for its on road consumption. For the whole aggregated volume of BEVs, $8\text{kWh} \times 1250 = 10\text{MWh}$ of battery energy capacity is reserved for on road consumption. The DOD is set as 90%, therefore, the total available battery energy capacity for the power grid is varying between 20MWh to 100MWh.

C. Probabilistic modelling of Aggregated volume (bulk volume) of BEVs

Alternatively, bulk volume of BEVs can be modelled probabilistically using Markov chain Monte Carlo simulation by incorporating the transportation survey data. In those modelling the charging and discharging probabilities, and vehicle availabilities due to transportation constraints including weather and congestion effects on roads are taken into account. Then the Markov chain is used to determine the availability of a vehicle at a time step of the Monte Carlo simulation and the number of vehicles at charging and discharging at each potential node of the distribution network. Thus, at each time step, the vehicle state is determined and at the convergence of Monte Carlo simulation, the transportation data given probabilities approximately equates the Monte Carlo simulation generated samples derived probabilities. [16-18]

III. Power system with integrated BEVs

Fig. 1 shows the power system that is used to investigate strategic benefits of BEVs in the presence of wind power generation and in the context of reliability enhancement. The system shown in Fig. 1 is a modified version of IEEE 24-bus Reliability Test System (RTS) [19]. IEEE 24-bus RTS is modified by introducing typical distribution network models without compromising the magnitudes of nodal load demands. The test system was expanded because the BEV stations are typically connected at distribution end of a power system and the expansion should reflect generic features of distribution networks. The northern part of the power transmission network has a voltage level of 230kV and the southern part consists of ten distribution feeders extended from 138kV buses to 33kV and 11kV buses. The distribution feeders have different configurations to represent network topological influence when BEVs are connected at different feeders.

The capacities of three conventional generators at bus 1, bus 2, and bus 7 are decreased to introduce five wind power generating stations at the distribution feeders. They were installed by extending the feeders from Bus 1, Bus 2, Bus 6, Bus 7, and Bus 8. The original IEEE 24-bus RTS has ten load points at 138kV buses. They are connected at the distribution feeders passing through 33kV and 11kV buses. All 11kV buses are considered as potential locations to connect stations of BEVs.

A. Load Profile

The loads at 230kV buses remain as in the original IEEE 24-bus RTS configuration. The original loads at 138kV buses are distributed over 33kV and 11kV buses. The loads at distribution feeders were modelled as three-phase unbalanced loads with a 20% variation of the load level between phases.

The original IEEE 24-bus RTS gives hourly, daily and weekly peak load variations for a year. Case study fitted the yearly load variation into 48 hourly load variations of each season. Fig. 2 shows the seasonal load variation that fits into 48 hours. In 48 hour load variation, hour 1 to 24 represent the weekday average hourly load value; while from hour 24 to 48 represent the weekend load behaviour. Thus, it results each season with different characteristics as shown in Fig. 2. Spring and autumn have a lower average load demand and in summer and winter, the load demand is much higher.

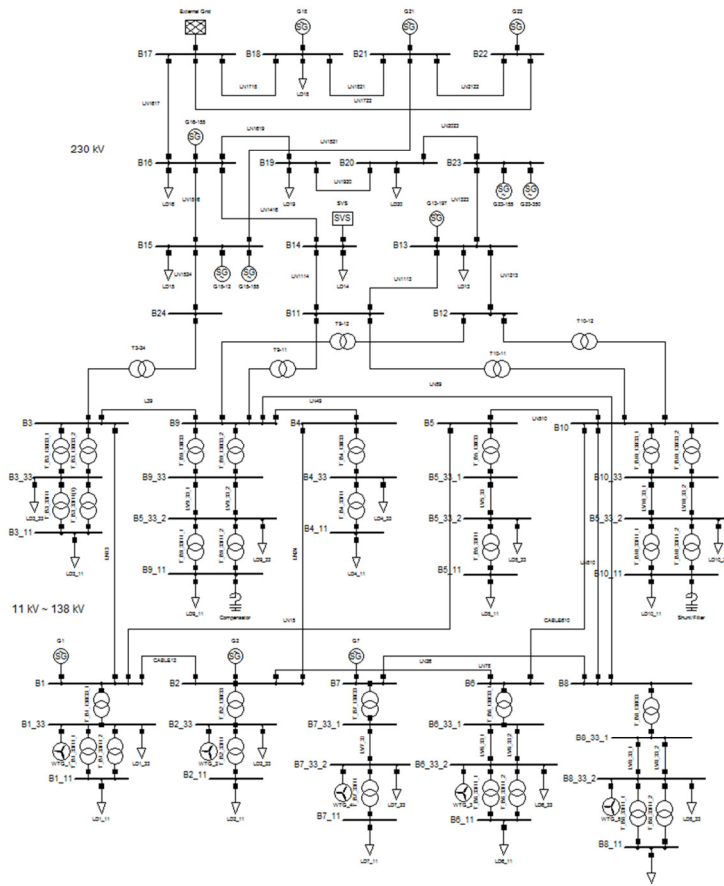


FIG. 1. Modified IEEE 24-Bus Reliability Test System.

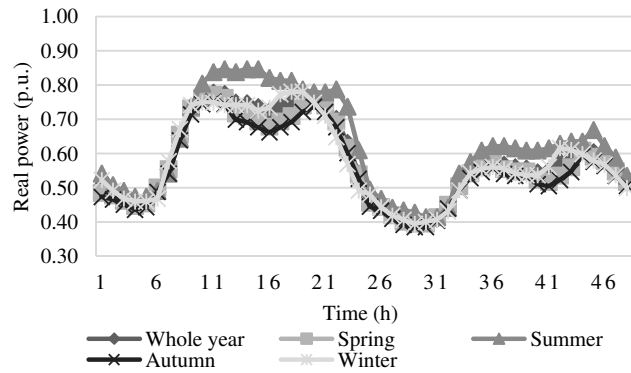


FIG.2. 48-hour load variations

B. Wind farm output profile

The whole year wind turbine output data is fitted into 48-hour profile. Fig. 3 shows the 48-hour active power profiles for seasons in a year. In Fig. 3, hourly samples are calculated by using the statistical wind profile data and then dividing the 8760 hours of samples into 12 clusters. Each cluster is then used to calculate the time series of wind outputs of seasons with the maximum output to the minimum and then back to the maximum again with medium ones in between.

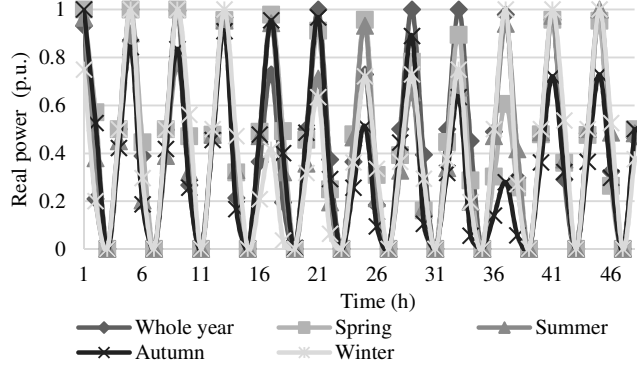


FIG. 3. 48-hour wind variations.

C. Correlation between wind regimes

It is reported that if wind farms are spaced out with certain distances, the correlation between them can be reduced [20]. According to the study carried out at a Ontario wind farm, the pair correlation between separated wind farms is determined by [21];

$$\text{Correlation factor, } C = Ae^{-S/S_0} \quad (7)$$

where, A and S_0 are constants, $A=0.993$ and $S_0=400$ km, S is the separation between wind farms in kilometers. From (7), the correlation factor decays exponentially with the decay length of 400 km. This means that according to the study carried out in [21], if the wind farm distances are less than 400 km, then they can be considered as highly correlated.

For the case studies, the geographical areas of five wind farms are divided into two regions with a distance of 80 km in between. Wind farms at Bus 1, Bus 2 and Bus 7 are in the regime A and wind farms at Bus 6 and Bus 8 are in regime B. Thus, using (7), the correlation factor for the output of Region B with respect to Region A is calculated as 0.813.

D. Wind power penetration levels

As projected in many counties and regions, the wind power will provide 20% or more of electricity generation by 2020 [22]. The capability of a power system to absorb such a growth of intermittent power while maintaining the reliability and availability is challenging. This paper investigates three levels of wind penetrations. They are wind penetration level of 10%, 15%, and 20% of total load demand. As the wind power increases, partial capacities of the conventional generators at Bus 1, Bus 2 and Bus 7 are phased out to investigate whether the renewable power can take the place of conventional power with the supports from BEVs. Specific details of wind and conventional generation capacity data are given in Table 1.

TABLE 1 WIND AND CONVENTIONAL GENERATION DATA

Wind penetration level	Total wind farm installed capacity (MW)	Total installed capacity of conventional generators connected at Bus 1, Bus 2 and Bus 7(MW)
0%	0	684
10%	955	399
15%	1433	257
20%	1918	112

E. 48-hour profile of BEVs

Surplus generation time series of the region that operates within the voltages of 138kV to 33kV and 11kV of modified IEEE 24-bus RTS is calculated using (1). In modified IEEE RTS, the total generation capacity is larger than the total peak load. The surplus generation time series calculation included the conventional generators connected at Bus 1, Bus 2 and Bus 7, five wind farms in the system, and the loads connected along the outgoing feeders of 138kV buses. Fig. 4 shows a sample of the calculated surplus generation for 48 hours.

Then, by using (1) to (6), samples of the SOC and output of BEVs for 48 hours are calculated and the results are shown in Fig. 5 and Fig. 6 respectively. The negative values of outputs of BEVs reflect the charging mode of BEVs whereas the positive values reflect the discharging mode of BEVs. The 48 hour output of BEVs is used to calculate reliability indices.

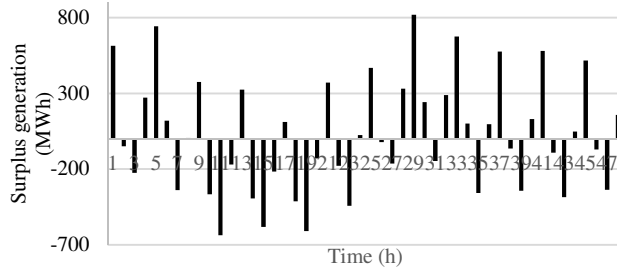


FIG. 4. 48-hour surplus generation.

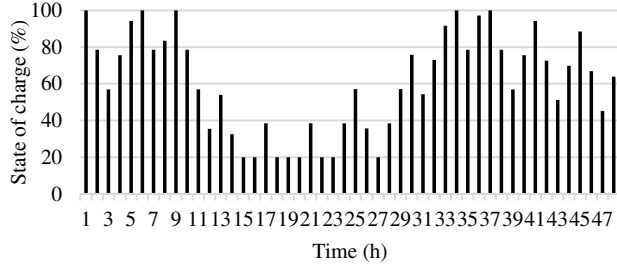


FIG. 5. 48-hour battery SOC

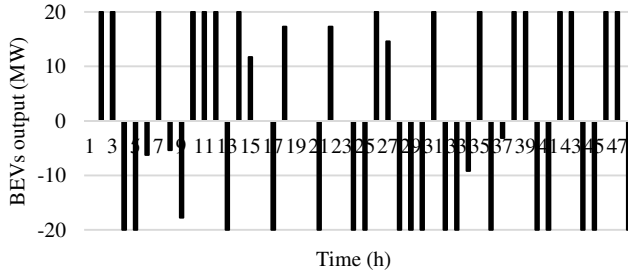


FIG. 6. 48-hour output of BEVs

IV. Reliability assessment

The reliability assessment proposed in this paper uses failure mode and effect analysis (FMEA) [23], by introducing unbalance operation in smart power systems. It analyzes the system components and identifies potential failures and their effects. The first step of the method is to generate a list of system states containing one or more simultaneous faults with a specific unbalance loading condition. Then, FMEA considers each system state and tries to re-supply interrupted loads by simulating the operators' reactions to the disturbance. The corrective measures used in this process include: 1) Fault clearance; 2) Fault separation; 3) Power restoration; and 4) Constraints alleviation by load transfer and load shedding as per the criticality of the problem. The results of FMEA applied to unbalanced operation are combined to give load point reliability indices. Then, system reliability indices are calculated using the load point indices.

The reliability index used in this paper is the Energy Not Supplied (ENS). ENS denotes the total amount of energy on average not delivered to the system loads. It can better represent the reliability differences between hours as ENS directly relates to the load variation as well as components failure rate and duration. Case studies consider BEVs are owned by the utility, electricity customers, or other organizations and they operate independently.

V. Scenario studies

A. Base scenario study

All the 11kV buses of ten distribution feeders are candidate nodes for BEVs. For the purpose of choosing strategic locations, at first all 11kV buses are connected with BEVs and reference ENS is calculated. Then, each aggregated volume of BEVs is disconnected at a time to simulate out of service situation and then ENS is calculated. Fig.7 shows the ENS results of this study. It can be noticed that when BEVs at feeder 7 are disconnected, the increase in ENS is much higher than the other feeders. Hence feeder 7 can be considered as the most strategic location for the connection of BEVs to reduce the un-supplying energy to electricity customers. If only a single aggregated volume of BEVs is to be used in the network, then it is recommended to

connect them at the feeder 7 to get the best reliability performance. Detail algorithm to determine strategic locations is shown in Fig. 8.

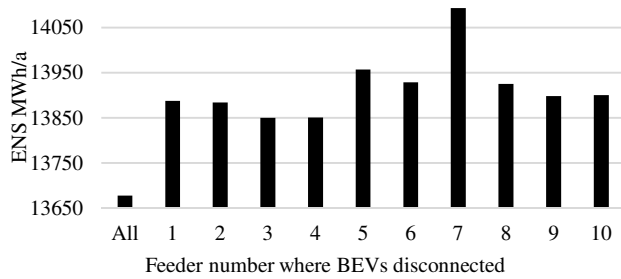


FIG. 7. ENS results with BEVs disconnected at some feeders

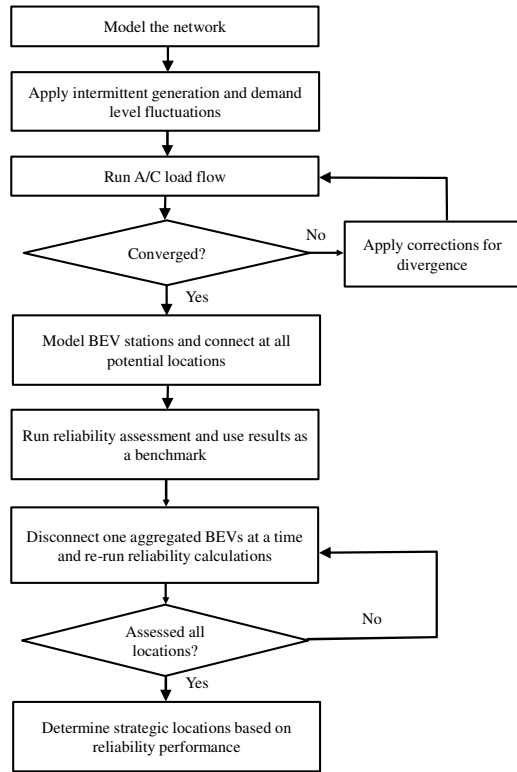


FIG. 8. Algorithm to determine strategic locations for BEVs.

Apply corrections for divergence works as follows. If the load flow solution diverges with the operating condition, then loads are shedded in small steps (5%), starting from the worst mismatch bus and to the point of achieving the convergence. This can result a blackout or partial blackout at a node or system wide at a critical operating stage. Then, the program determines the feasible level of load for the network pertaining to the operating condition of the time step.

B. Other scenario studies

1) Scenario 1: different charging and discharging rates

This study is carried out by taking into account the whole year load and wind patterns and then connecting BEVs at feeder 7. The aggregated volume of BEVs is at the fully charged mode (100MWh) at the beginning of 48 hours. The fast charging and discharging rates of bulk volumes are set as -20MW and $+20\text{MW}$ respectively, while slow charging and discharging rates of bulk volumes are set as -10MW and $+10\text{MW}$ respectively.

The results in Fig. 9 argue that if no BEVs are connected, ENS is impacted significantly because of the increased penetration levels of wind. After connecting BEVs and when the wind penetration level reached a 20%, the ENS was dropped. Results also suggest that the slow charging and discharging levels offer a lower level of ENS compared with fast charging levels. The reason to experience this variation is that more energy is lost during the fast-rate charging and discharging cycles. However, slow rate gives a less energy exchange and a less active power export when BEVs in operation as generators.

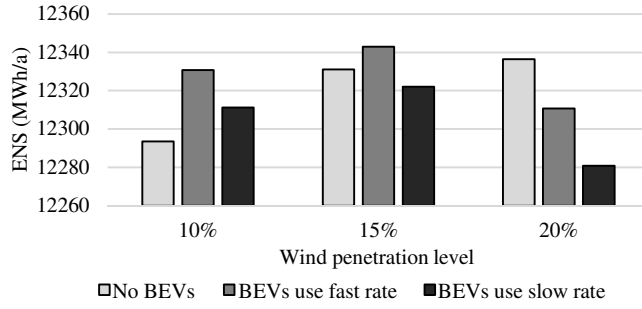


FIG. 9. Fast rate versus slow rate.

2) Scenario 2: different battery capacities

The case studies considered that one aggregated volume of BEVs has the total battery capacity of 100MWh, consisting of 1250 BEVs. However, the number of total BEVs connected to the same location can be varied from time to time, as some BEVs may be disconnected from the grid for on road use purposes while other BEVs may be connected to the grid. Therefore, this scenario relaxed the upper capacity limit of the battery bank. The initial stored energy is set at 100MWh and the charging and discharging rates are set as -20MW and 20MW respectively.

The 48-hour ENS results in Fig.10 suggest that when the wind penetration level is at 10%, the ENS of the case that considered no upper capacity limit for the battery is increased compared with the case of 100MWh capacity limit. However, an opposite argument was resulted when the wind penetration level reached a 20% of the total level. The reason behind this variation is that when the wind penetration level increases, increased battery capacity had a spare capacity to absorb the surplus energy which provided an additional support to the grid when the grid power generation was low.

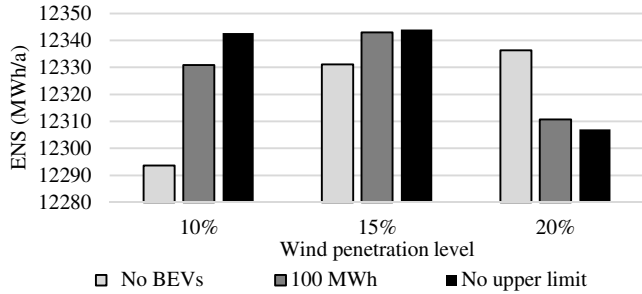


FIG. 10. ENS for the comparison of battery capacity

3) Scenario 3: Distributed connection of aggregated volume BEVs

The previous studies only considered a single aggregated volume of BEVs at feeder 7. This scenario takes into account distributed connection of aggregated volumes of BEVs at the remaining 11kV buses. Each aggregated volume BEVs has 100MWh battery capacity with -20MW and 20MW of maximum charging and discharging rates respectively. The surplus generation is equally used by each aggregated volume of BEVs. The study is carried out for the entire year, capturing wind and load pattern variations.

The results in Fig. 11 argue that under different wind penetration levels, the distributed connection of BEVs affects ENS; however, they are not consistent over the penetration levels. Thus, one can argue that a quantitative assessment is needed to calculate the threshold levels of distributed connection of BEVs with respect to the penetration level of wind. For example, for a 10% ~15% penetration level of wind, even with strategic operation, it does not result a reliability improvement; in fact, it is a worsening operating condition in the context of reliability enhancements. However, presence of 20% of wind with a single or two BEV stations result an improved level of reliability.

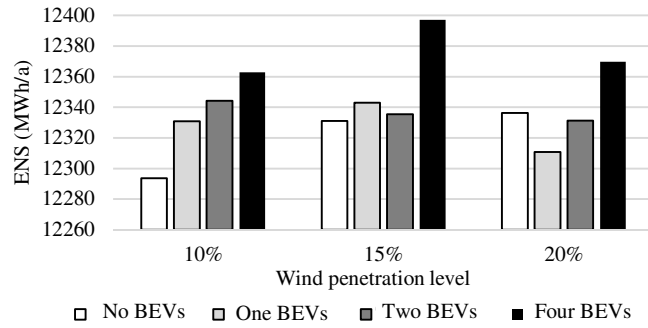


FIG. 11. ENS with different quantity of aggregated volume of BEVs

4) Scenario 4: Seasonal influence

Seasonal wind power and load demand vary distinctively. Fig. 12 shows 48-hour results of ENS improvement, calculated by using one aggregated volume of BEVs connected at feeder 7, to determine the percentage improvement of ENS, compared to without connection of BEVs. Positive percentage gives ENS is lower without the connection of BEVs. For the spring and autumn, the ENS reduction is significant when the wind penetration level is 15%, while for the summer and winter; the ENS reduces when the wind penetration level increases to 20%. The average load demand is at the highest level in summer and in winter while lowest level in spring and autumn. For a lower power demand in spring and autumn, 15% of wind penetration level is enough to supply the load demand of this network. The results also suggest that although the load demand in summer and in winter is high, the reliability performance of the power system can be improved by the strategic operation of BEVs.

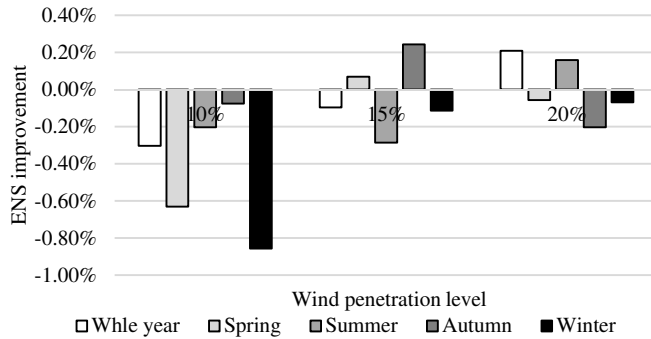


FIG. 12. ENS improvements under four seasons.

5) Scenario 5: Extreme conditions

When wind generation ratio reaches a certain level while the conventional generation is partially phased out, the network may face a risk that without wind power, the total generation may not be able to meet the load demand and the power system can potentially be collapsed. A sample reliability assessment is carried out with a different number of aggregated volumes of BEVs in use, to determine the support of BEVs that can bring to the grid when wind output is zero. This study uses 20MW fixed output for each aggregated volume of BEVs to run the reliability assessment. Details of assessment results are shown in Table 2, where 'collapse' refers to a voltage collapse condition whereas 'safe' refers to a feasible operating condition.

TABLE 2 EXTREME CONDITIONS

Wind penetration level	Number of aggregated volume of BEVs in use				
	0	1	4	8	10 (all)
10%	Safe	Safe	Safe	Safe	Safe
15%	Collapse	Collapse	Safe	Safe	Safe
20%	Collapse	Collapse	Collapse	Collapse	Safe

The results argue that with a wind penetration level of 10%, the system can manage the loss of power generation from BEVs. When wind generation capacity reaches 15%, system moves to a voltage collapse condition if none or only one aggregated volume of BEVs is connected. For the 20% wind penetration level, all aggregated volumes of BEVs are to be connected to support the extreme conditions.

The application of the proposed approach requires the presence of smart control and coordination of devices in the power system. With the advances in smart grid technologies, the power systems transform their operating paradigms to smart grid led smart operation. Thus, the futuristic power systems should see the benefits of the proposed approach considerably.

VI. Remarks

In the context of current state of a power grid, the charging/discharging decisions are mainly dependent on the availability of BEVs and customers' preferences. BEVs need to be charged when the customers plug in their cars, irrespective on the supply availability. Accordingly, utilities have to optimize their energy production to meet BEV variable charging demands, dependent on customers' preferences and habits.

However, the paper considers that the electric vehicles operate in a context of smart grids, where the customers are also treated as active customers. There will be variety of business models at the customer's side and the network operator's side and both of them competes each other. They all are coordinated and controlled optimally in near real-time for the benefit of economical, secure, and efficient operation of the smart power grid. The paper does not specifically detail how the active customer operation takes place in a smart grid context however; it incorporates the benefits of such operation for the reliability improvement in a smart grid.

VII. Conclusions

This paper proposes a time-sequential approach to determine the strategic locations of BEVs and to enhance the reliability performances of a wind-integrated unbalanced smart power system. The approach characterizes the operation of BEVs based on the level of intermittency produced by the distributed generation, level of fluctuation by the load demand, and on their road activities in time sequence.

Investigations depicted that the strategic locations of BEVs are mainly influenced by network architecture, level of fluctuation in load demand, and the level and the location of penetration of intermittent distributed generation. Reliability performance of an unbalanced power system can potentially be improved by the bulk and strategic connection of BEVs; however the level of improvement also depends on the level of intermittency produced by distributed generation. There are critical penetration levels of intermittent distributed generation to an unbalanced power system and beyond which reliability-performance can be improved by the strategic operation of BEVs. The proposed approach computes the critical thresholds of intermittent distributed generation and the levels of needed BEVs.

With the increased presence of intermittent distributed generation in smart power distribution systems, the standing reserve supports from conventional units are not always justified in an economic sense. In such context, the proposed approach can be used as an alternative to calculate breakeven points of conventional reserve over strategic BEVs to better serve the electricity to active customers.

References

- ¹Acha, S., Green, T.C., and Shah, N., 'Effects of Optimised Plug-in Hybrid Vehicle Charging Strategies on Electric Distribution Network Losses', in, *Transmission and Distribution Conference and Exposition, IEEE PES*, (2010)
- ²Marra, F., Yang, G.Y., Fawzy, Y.T., Traholt, C., Larsen, E., Garcia-Valle, R., and Møller Jensen, M., 'Improvement of Local Voltage in Feeders with Photovoltaic Using Electric Vehicles', *IEEE Trans. Power Syst.*, 2013, 28, (3), pp. 3515-3516.
- ³Ghanbarzadeh, T., Baboli, P.T., Rostami, M., Moghaddam, M.P., and Sheikh-El-Eslami, M.K., 'Wind Farm Power Management by High Penetration of Phev', in, *Power and Energy Society General Meeting, IEEE PES*, (2011)
- ⁴Lund, H. and Kempton, W., 'Integration of Renewable Energy into the Transport and Electricity Sectors through V2g', *Energy Policy*, 2008, 36, (9), pp. 3578-3587.
- ⁵Ma, Y., Houghton, T., Cruden, A., and Infield, D., 'Modeling the Benefits of Vehicle-to-Grid Technology to a Power System', *IEEE Trans. Power Syst.*, 2012, 27, (2), pp. 1012-1020.
- ⁶Jayaweera, D., Islam, S., and Neduvélil, S., 'Two-Stage Approach for the Assessment of Distributed Generation Capacity Mixture in Active Distribution Networks', *Journal of Renewable and Sustainable Energy*, 2013, 5, p. 053120.
- ⁷Jayaweera, D. and Islam, S., 'Value Based Strategic Integration of Distributed Generation ', in, *Australasian Universities Power Engineering Conference (AUPEC)*, (2010)
- ⁸Cheng, L., Chang, Y., Lin, J., and Singh, C., 'Power System Reliability Assessment with Electric Vehicle Integration Using Battery Exchange Mode', *IEEE Transactions on Sustainable Energy*, 2013, 4, (4), pp. 1034-1042.
- ⁹Kempton, W. and Tomić, J., 'Vehicle-to-Grid Power Implementation: From Stabilizing the Grid to Supporting Large-Scale Renewable Energy', *Journal of Power Sources*, 2005, 144, (1), pp. 280-294.
- ¹⁰Bangalore, P. and Bertling, L., 'Extension of Test System for Distribution System Reliability Analysis with Integration of Electric Vehicles in Distribution System', in, *Innovative Smart Grid Technologies (ISGT Europe), IEEE PES International Conference and Exhibition on*, (2011)
- ¹¹Bangalore, P.: 'Development of Test System for Distribution System Reliability Analysis, Integration of Electric Vehicles into the Distribution System', Master's Thesis, Chalmers University OF Technology, (2011)
- ¹²Billinton, R., 'A Sequential Simulation Method for the Generating Capacity Adequacy Evaluation of Small Stand-Alone Wind Energy Conversion Systems', in, *Electrical and Computer Engineering, 2002. IEEE CCECE 2002. Canadian Conference on*, (2002)

- ¹³Hu, P.S. and Young, J.R., 'Summary of Travel Trends: 1995 Nationwide Personal Transportation Survey', (1999)
- ¹⁴Kempton, W., Tomic, J., Letendre, S., Brooks, A., and Lipman, T., 'Vehicle-to-Grid Power: Battery, Hybrid, and Fuel Cell Vehicles as Resources for Distributed Electric Power in California', (Institute of Transportation Studies, UC Davis, 2001)
- ¹⁵<http://www.teslamotors.com/>, accessed Date Accessed 2013 Accessed
- ¹⁶Darabi, Z.; Ferdowsi, M., "Plug-in hybrid electric vehicles: Charging load profile extraction based on transportation data," Power and Energy Society General Meeting, 2011 IEEE , vol., no., pp.1,8, 24-29 July 2011
- ¹⁷ElNozahy, M.S.; Salama, M.M.A., "A Comprehensive Study of the Impacts of PHEVs on Residential Distribution Networks," Sustainable Energy, IEEE Transactions on , vol.5, no.1, pp.332,342, Jan. 2014
- ¹⁸D. Jayaweera, S. Islam "Risk of Supply Insecurity with Weather Condition Based Operation of PHEVs", IET Generation, Transmission, and Distribution, Vol. 8, No. 12, p. 2153 – 2162, December 2014
- ¹⁹Grigg, C., Wong, P., Albrecht, P., Allan, R., Bhavaraju, M., Billinton, R., Chen, Q., Fong, C., Haddad, S., and Kuruganty, S., 'The Ieee Reliability Test System-1996. A Report Prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee', *IEEE Trans. Power Syst.*, 1999, 14, (3), pp. 1010-1020.
- ²⁰Jayaweera, D., Wee, R.C., and Islam, S., 'Security of Supply with Dispersed Integration of Wind Power in Distribution Networks', in, *Australasian Universities Power Engineering Conference (AUPEC)*, (2011)
- ²¹Harrison, J., 'Correlation of Ontario Wind Farm Power Output with Wind Farm Separation', (2008)
- ²²2012 Iea Wind Annual Report', (International Energy Agency, 2013)
- ²³Billinton, R. and Allan, R.N., *Reliability Evaluation of Power Systems*, (Plenum press New York, 1996)